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# NEUTRINOS & BARYOGENESIS \*

Conditions for baryo- /  
leptogenesis

Thermal leptogenesis

Connection with neutrino masses

work with

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## (i) Conditions for baryo-/leptogenesis

observed cosmological baryon density , i.e. matter - antimatter asymmetry , from CMB (BOOMERang , DASI)

$$Y_B = \frac{n_B}{n_\gamma} = (6.0 \begin{array}{l} +1.1 \\ -0.8 \end{array}) \times 10^{-10}$$

related to fundamental symmetries ; provides important relation between cosmology and extension of the S.M. , i.e. neutrino physics , ...

Sakharov's conditions for a dynamical generation of the baryon asymmetry :

- $\beta$ -violation
  - sphaleron processes , L-violation
- C- and CP - violation
  - neutrino properties
- deviation from thermal equilibrium
  - decay of heavy Majorana neutrinos

## Sphaleron processes

lead to effective interaction of all left-handed fermions in S.M. ('t Hooft),

$$O_{B+L} = \prod_i (q_L^i q_L^i \bar{q}_L^i \bar{q}_L^i)$$

which violate B- and L-number with

$$\Delta B = \Delta L = 3$$

they are in thermal equilibrium (Kuzmin, Rubakov, Sveshnikov) in the temperature range

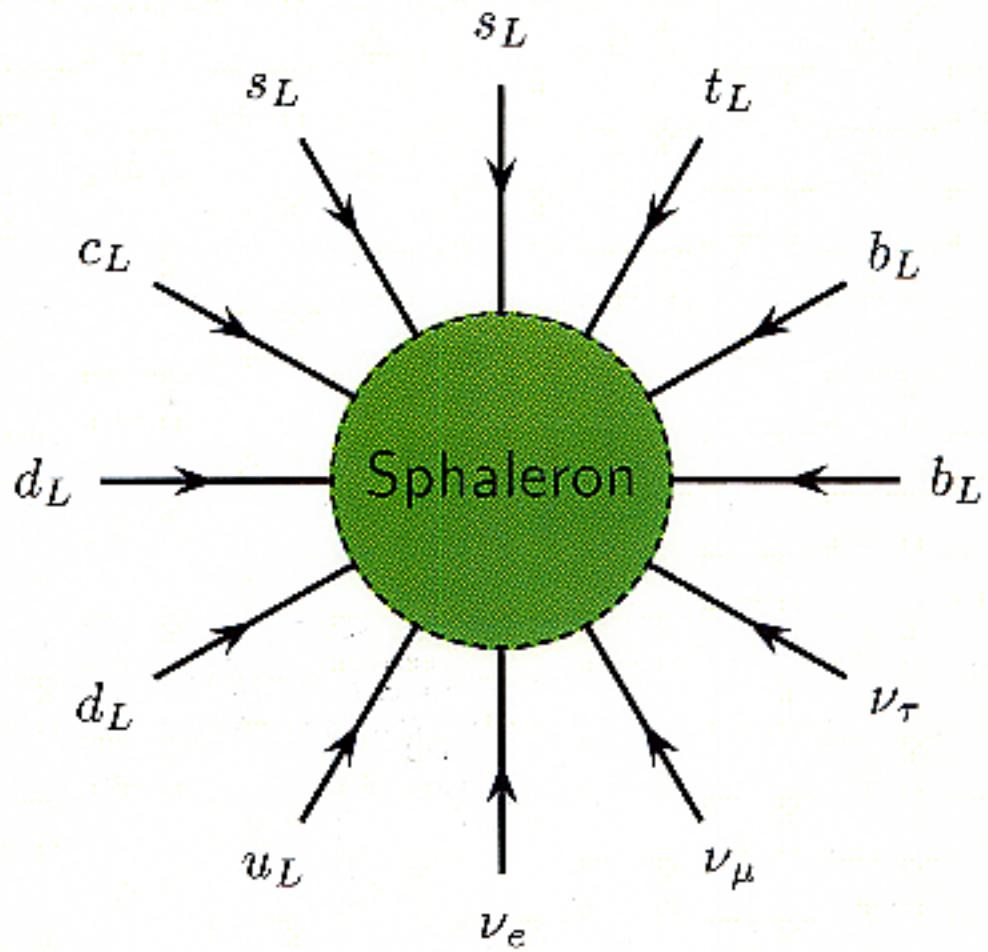
$$T_{\text{ew}} \sim 100 \text{ GeV} < T < T_{\text{SPH}} \sim 10^{12} \text{ GeV}$$

In thermal equilibrium, this leads to a relation between asymmetries in B- and L-number,

$$\boxed{(\Delta B)_T = c_s (\Delta L)_T},$$

where  $c_s = -8/15$  in SM with 2 Higgs doublets

→ Baryogenesis requires lepton-number violation - but not too much !



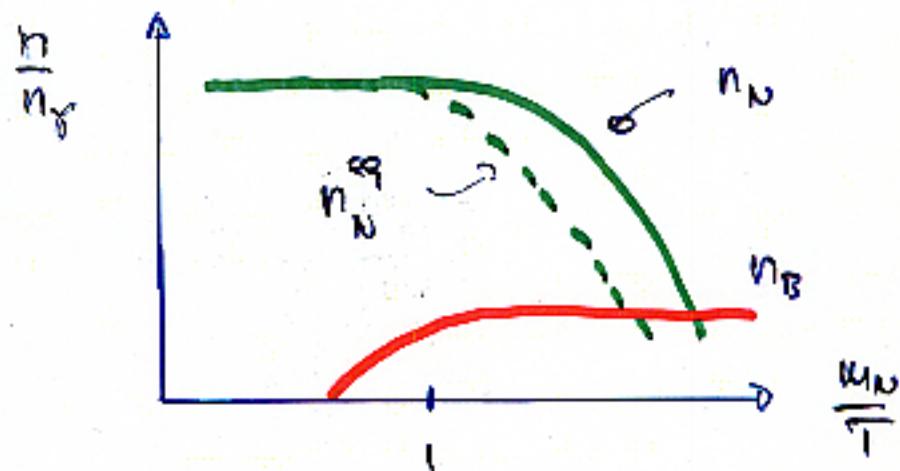
Simplest realisation : Majorana neutrinos  
and seesaw mechanism,

$$L_H = h_{ij} \bar{\ell}_{Li} \nu_{Rj} \phi + \frac{1}{2} M_{ij} \bar{\nu}_{Ri}^c \nu_{Rj} + \text{h.c.}$$

$$\Delta L = 2$$

mass eigenstates, light :  $\nu_i \approx \nu_{Li} + \nu_{ci}^c$  and  
heavy :  $N_i \approx \nu_{Ri} + \nu_{Bi}^c$  Majorana neutrinos

Delayed decays of heavy neutrinos ( $N$ ) yields  
lepton asymmetry and, via sphaleron processes,  
baryon asymmetry (Fukugita, Yanagida) :



→ stringent constraints on neutrino properties !

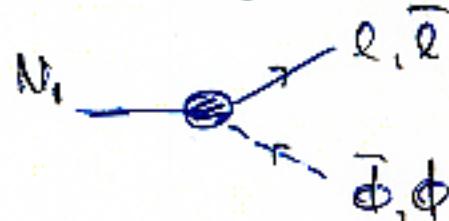
Other varieties of leptogenesis : Affleck-Dine ,  
inflationary decays , preheating , brane collisions ,  
 $B$ -dominated universe , ...

## (2) Thermal leptogenesis

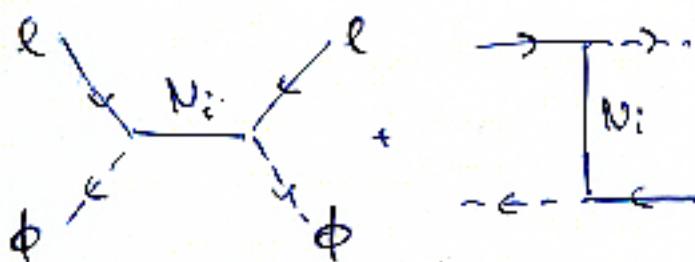
Consider electroweak plasma with heavy Majorana neutrinos ( $N_i$ ) ; relevant processes at high temperatures (Luty, Plimack, ...):

decays (D) and inverse decays (ID):

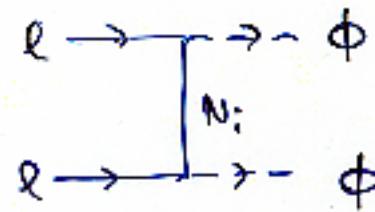
$$N_i \leftrightarrow l\bar{\phi}, \bar{l}\bar{\Phi}$$



$\Delta L = 2$  processes ( $N_i$ : real + virtual):

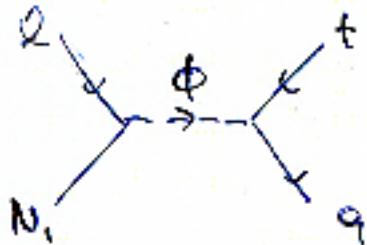


$$l\bar{\phi} \leftrightarrow \bar{l}\phi \text{ (N)}$$



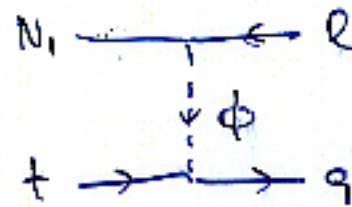
$$\begin{aligned} ll &\leftrightarrow \phi\phi \\ \bar{l}\bar{l} &\leftrightarrow \bar{\phi}\bar{\phi} \quad (\text{virt}) \end{aligned}$$

$\Delta L = 1$  scatterings:



$$N_i l(\bar{l}) \leftrightarrow \bar{t}(t) q(\bar{q})$$

(phi,s)



$$N_i t(\bar{t}) \leftrightarrow \bar{l}(l) q(\bar{q})$$

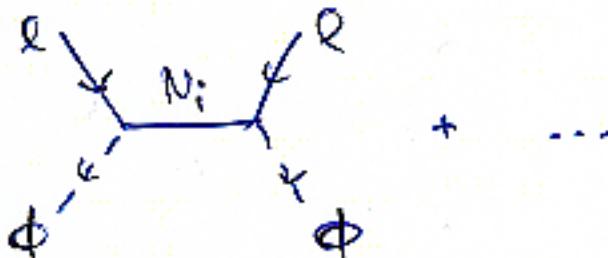
(phi,t)

## Crucial property of scattering rates :

$$\frac{\Gamma_i}{H}, \frac{\Gamma_N^{\text{res}}}{H} \propto \frac{\tilde{m}_i}{v^2}, \quad \text{Higgs vev}$$

$$\boxed{\tilde{m}_i} = \frac{(w_0^+ w_0^-)_{ii}}{M_i}, \quad w_0 = h v, \quad v = \langle \phi \rangle$$

off-shell part of  $\Delta L = 2$  process ,



$$\Gamma_N = \Gamma_N^{\text{res}} + \Delta \Gamma_N,$$

$$\frac{\Delta \Gamma_N}{H} \propto \frac{M_i \bar{m}^2}{v^4}, \quad \boxed{\bar{m}^2} = \text{tr}(w_0^+ w_0^-) = \sum_i w_i^2$$

In thermal leptogenesis the generated baryon asymmetry depends just on 4 parameters :

$$\text{CP-asymmetry : } \epsilon_i = \frac{\Gamma(N_i \rightarrow l \bar{\phi}) - \Gamma(N_i \rightarrow \bar{l} \phi)}{\Gamma(N_i \rightarrow l \bar{\phi}) + \Gamma(N_i \rightarrow \bar{l} \phi)}$$

mass of 'decaying' heavy neutrino :  $M_i$

light neutrino masses :  $\tilde{m}_i, \bar{m}$

no additional dependence on masses or mixings !

figure 1a

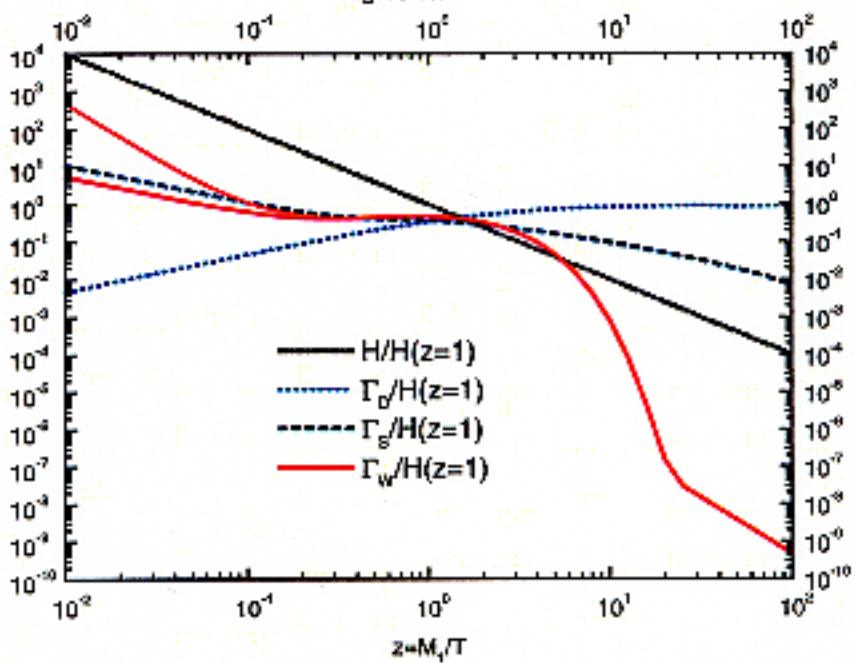
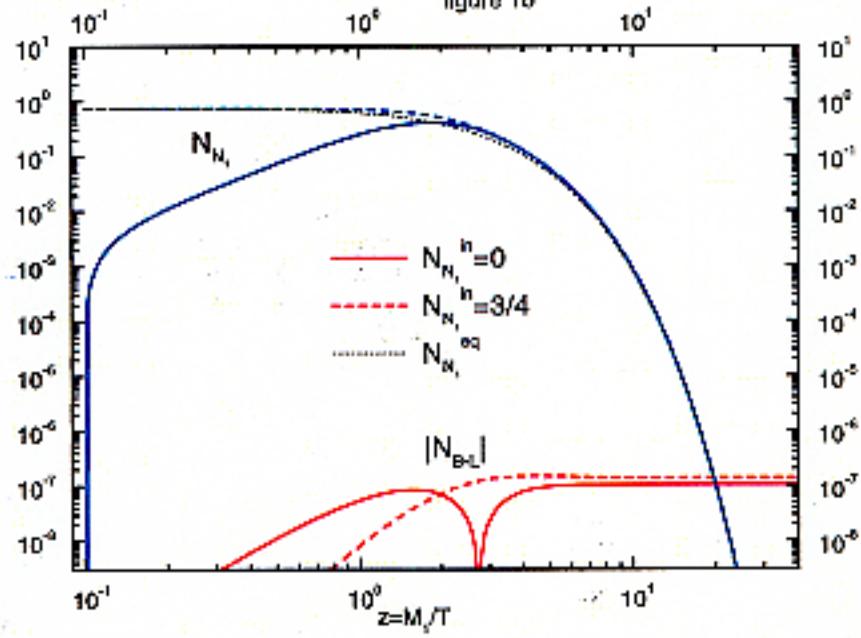


figure 1b



$$E_L \approx -10^{-6} ; \quad M_1 \approx 10^{10} \text{ GeV} , \quad \tilde{m}_1 = 10^{-3} \text{ eV}$$

$$\tilde{m} = 0.05 \text{ eV}$$

figure 2a

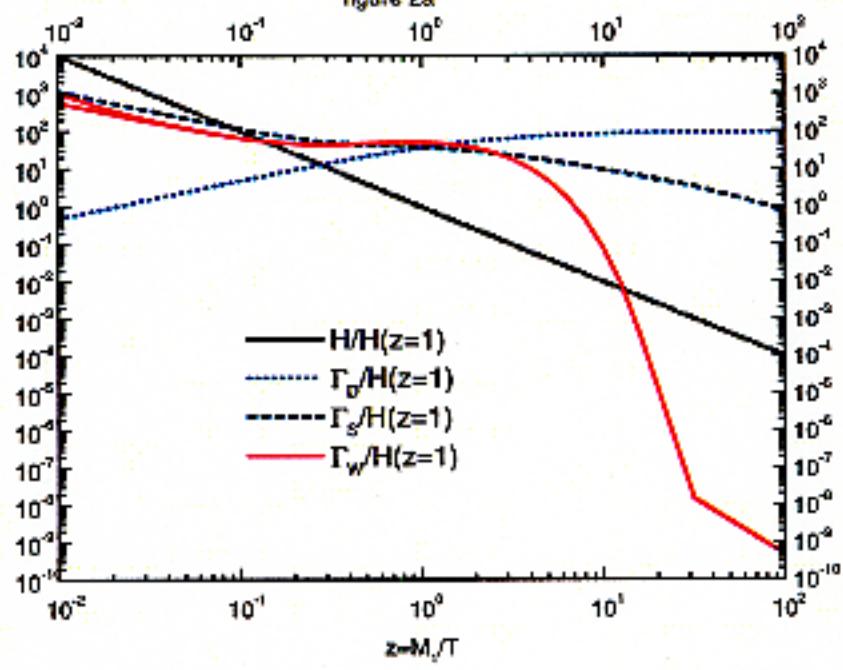
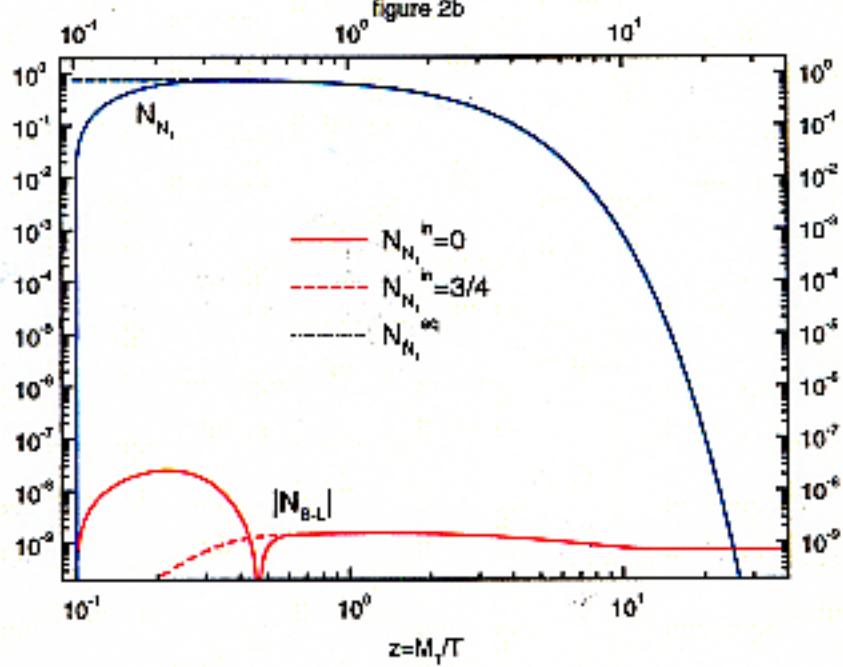


figure 2b



$$\epsilon_1 \approx 10^{-6} ; \quad M_1 = 10^{10} \text{ eV} , \quad \tilde{M}_1 = 10^{-1} \text{ eV} ,$$

$$\bar{M} = 0.05 \text{ eV}$$

figure 3a

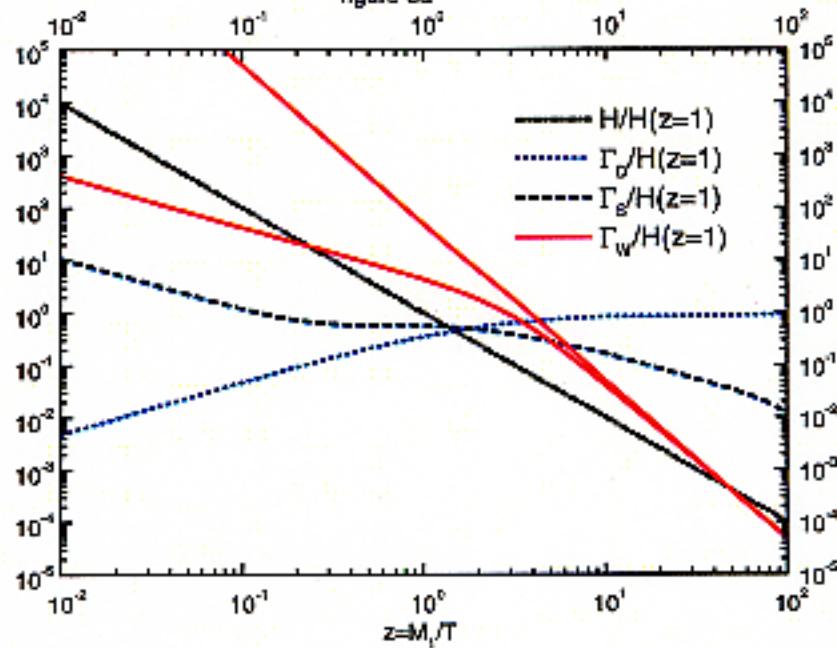
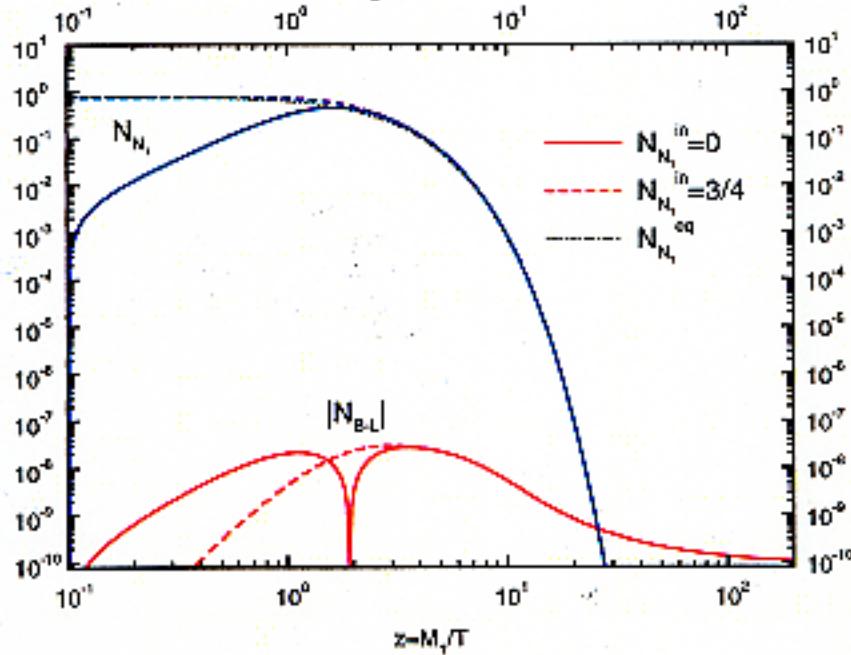


figure 3b



$$\epsilon_1 \approx -10^{-6} ; \quad M_1 \approx 10^{15} \text{ GeV} , \quad \tilde{m}_1 = 10^{-3} \text{ eV} ,$$

$$\tilde{m} = 0.05 \text{ eV}$$

### (3) Connection with neutrino masses

Thermal leptogenesis leads to bounds on neutrino masses,  $\tilde{m}_i < \tilde{m}_i^{\text{max}}$ ,  $M_i > M_i^{\text{min}}$ ; recently, model independent bound on CP asymmetry from seesaw mechanism (Davidson, Ibarra); seesaw mass relation:

$$m_\nu = - m_3 \frac{1}{M} \tilde{m}_3^\top, \quad m_3 = h v ;$$

CP asymmetry (Car, Roulet, Vissani, ...):

$$\epsilon_1 \approx - \frac{3}{16v} \frac{M_1}{(h^\dagger h)_\parallel} \text{Im} \left( h^\dagger h \frac{1}{M} h^\dagger h^* \right)_\parallel$$

one can derive upper bound on  $\epsilon_1$ :

$$(\epsilon_1)^l \leq \epsilon(M_1, \tilde{m}) = \frac{3}{16v} \frac{M_1}{g^2} \frac{m_{\text{atm}}^2 + m_{\text{sol}}^2}{m_3},$$

$$m_3^2 = \frac{1}{3} (\tilde{m}^2 + 2 m_{\text{atm}}^2 + m_{\text{sol}}^2)$$

$$m_2^2 = \frac{1}{3} (\tilde{m}^2 - m_{\text{atm}}^2 + m_{\text{sol}}^2)$$

$$m_1^2 = \frac{1}{3} (\tilde{m}^2 - m_{\text{atm}}^2 - 2 m_{\text{sol}}^2)$$

sensitivity on absolute neutrino mass scale !

Successful leptogenesis requires

$$\eta_B^{\max}(\tilde{m}_1, M_1, \tilde{m}) = \eta_B(\tilde{m}_1, M_1, \tilde{m}; \varepsilon_i) \Big|_{\varepsilon_i = \varepsilon(M_1, \tilde{m})}$$
$$\geq \eta_B^{\text{CHB}}$$

numerical analysis of Boltzmann eqs. yields

$$M_1 > 4 \times 10^8 \text{ GeV}, \quad \boxed{m_1 < 0.2 \text{ eV}}$$

will be tested by KATRIN, GENIUS, ... , cosmology!

Direct test of leptogenesis + seesaw mechanism!

Simpliest theoretical picture,  $U(1)_{B-L} \subset G_{422} \subset SO(10)$

broken at  $\Lambda_{\text{GUT}}$  with hierarchical neutrinos,

yields correct order of magnitude for baryon

asymmetry without fine-tuning of parameters

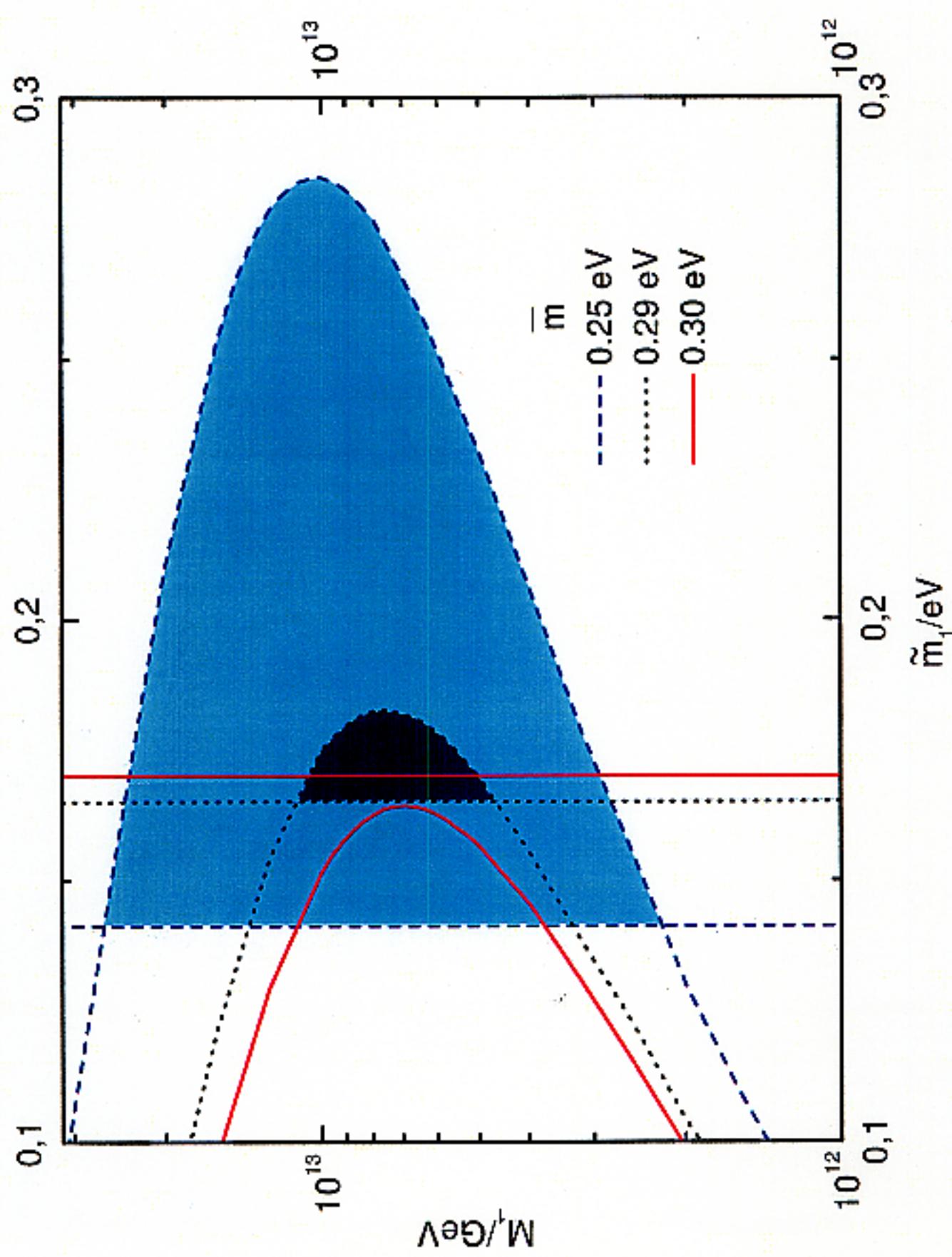
(WB, Plimack)

$$m_3 \sim \frac{v^2}{M_3} \sim 0.01 \text{ eV}, \quad M_3 \sim 10^{15} \text{ GeV}$$

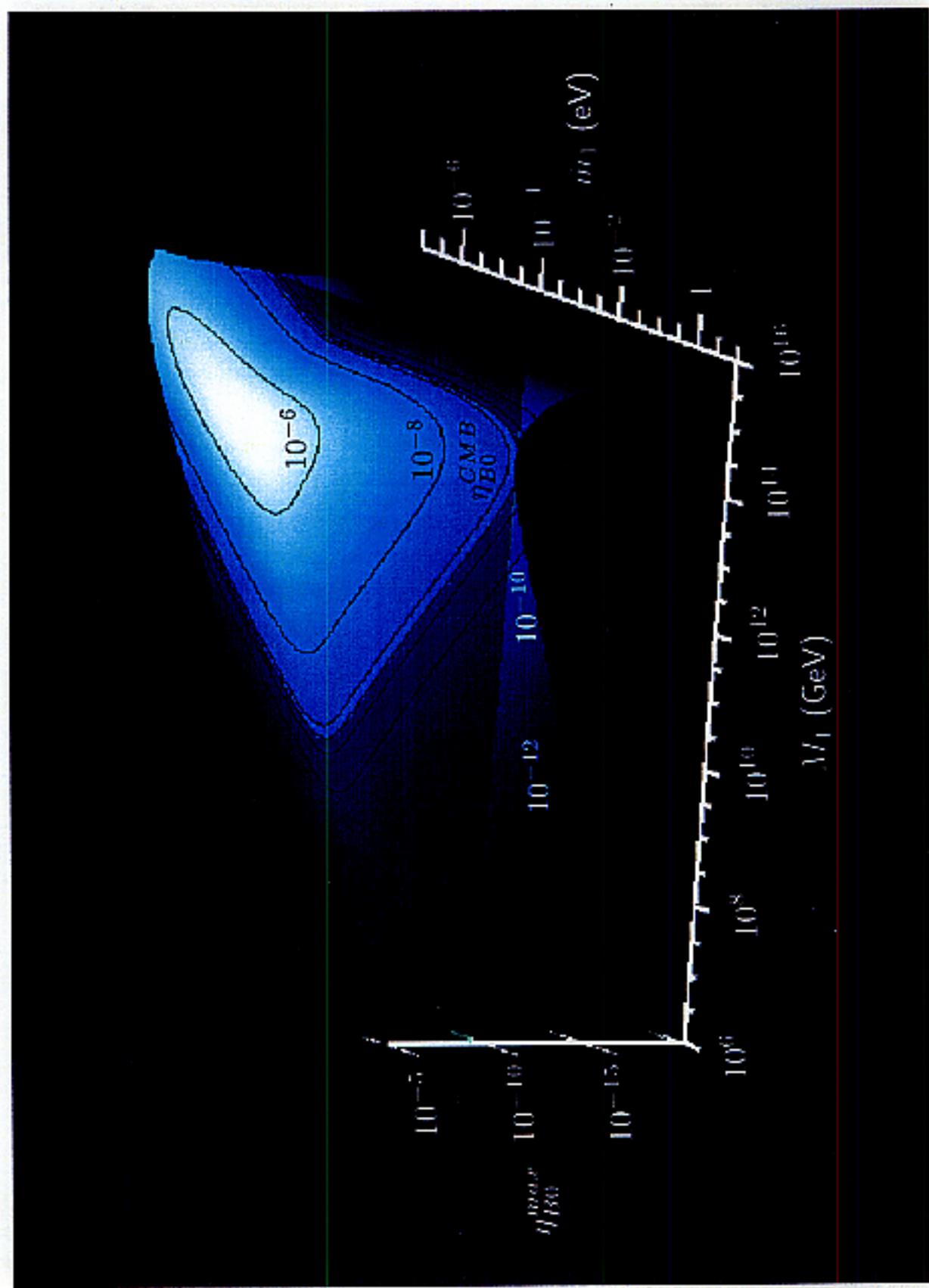
$$\rightarrow M_1 \sim T_B \sim 10^{10} \text{ GeV}, \quad \varepsilon \sim 0.1 \frac{M_1}{M_3} \sim 10^{-6},$$

$$\eta_B \sim K \cdot 10^{-2} \cdot 10^{-6} \sim 10^{-9} \quad (\text{K=0.1 worked out}),$$

upper bound on CP asymmetry saturated in many models



$$\overline{m} = 0.05 \text{ eV}$$



## SUMMARY

- (i) Baryogenesis requires lepton-number violation and Majorana neutrinos
- (ii) The upper bound on neutrino masses,  
 $m_i < 0.2 \text{ eV}$ ,  
is a direct test of leptogenesis +  
seesaw mechanism
- (iii) Large baryogenesis temperature,  $T_B \sim 10^{10} \text{ GeV}$ ,  
has consequences for dark matter problem  
(gravitinos)
- (iv) Theoretical development beyond  
Boltzmann eqs. needed